Arc-second alignment and bonding of International X-Ray Observatory mirror segments

Tyler C. Evans*[a,b], Kai-Wing Chan[b,c], Ryan McClelland[a], Timo Saha[d]
[a]SGT, Inc, 7701 Greenbelt Road Suite 400, Greenbelt, MD 20770, USA;
[b]X-Ray Astrophysics Laboratory, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA;
[c]Center for Research and Exploration in Space Science and Technology & Center for Space Science and Technology, University of Maryland, Baltimore County, Baltimore, MD 21250, USA;
[d]Optics Branch, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

ABSTRACT

The optics for the International X-Ray Observatory (IXO) require alignment and integration of about fourteen thousand thin mirror segments to achieve the mission goal of 3.0 square meters of effective area at 1.25 keV with an angular resolution of five arc-seconds. These mirror segments are 0.4 mm thick, and 200 to 400 mm in size, which makes it hard not to impart distortion at the sub-arc-second level. This paper outlines the precise alignment, verification testing, and permanent bonding techniques developed at NASA's Goddard Space Flight Center (GSFC). These techniques are used to overcome the challenge of aligning thin mirror segments and bonding them with arc-second alignment and minimal figure distortion. Recent advances in technology development in the area of permanent bonding have produced significant results. This paper will highlight the recent advances in alignment, testing, and permanent bonding techniques as well as the results they have produced.

Keywords: X-Ray optics, International X-Ray Observatory, IXO telescope, mirror alignment, mirror bonding

1. INTRODUCTION

Aligning thin glass segments used for the optics of the International X-Ray Observatory (IXO) poses an interesting challenge. IXO is a project designed at building upon the success of previous x-ray missions such as Chandra and XMM Newton. (For IXO mission background, see [1]). It will have a much larger effective area than any previous x-ray mission with 3.0 square meters at 1.25 keV with an angular resolution of five arc-seconds. The designed double reflection focal length of the system is 20 meters (previously mission goals called out 8.4 meters). Because IXO is going to operate in the x-ray spectrum, grazing incidence optics are required where the x-ray photons deflect off the mirror at about a 1 degree angle. A Wolter-I type telescope design was selected where the incoming x-ray photons graze off of a primary mirror and a secondary mirror at a very small angle to get to the detector. There are several segments nested close together to maximize effective area. The nested mirror segments were selected to be 0.4 mm thick to conserve mass and maximize collecting area. Meeting the angular resolution requirement of five arc-seconds with such thin glass segments presents a challenge.

To accommodate all of the mirrors for the telescope, a modular design was conceived. The Flight Mirror Assembly[2] (FMA) will support 60 modules arranged in three rings, 12 inner, 24 middle, and 24 outer. There will be 200 to 280 mirror segments per module for a total of about fourteen thousand mirror segments. The primary and secondary mirrors must be aligned to each other to meet the strict angular resolution requirement. In addition, all of the mirror pairs must focus to the same point within the required resolution. The mirror segments being used are made by slumping flat glass onto polished mandrels[5]. The mirror segments are 200 mm long in the axial direction and have a circumferential span of up to 360 mm. This makes each mirror about the size of a standard piece of 8.5" by 11" paper, and about four pieces of paper thick.

*Tyler.Evans@nasa.gov; phone 1 301 286-2677; ixo.gsfc.nasa.gov

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There are currently three approaches being developed to solve the challenge of aligning and mounting the mirror segments into a permanent structure. In the first approach, the mirror is adjusted with small high resolution linear actuators to correct for axial and figure errors[3]. This method is being pursued by a team at the Smithsonian Astrophysical Observatory (SAO). The second method involves forcing the mirror segment into a prescribed geometry[4]. This approach is being investigated at the European Space Agency (ESA) and associated industries. The third method is to preserve the fabricated state of the mirror and not introduce any distortion or figure error throughout the alignment and mounting processes. This third method, known as the suspension mount, is being developed at NASA's Goddard Space Flight Center (GSFC) and will be discussed in this paper.

2. SUSPENSION MOUNT PROCESS

For the suspension mount method, there are five major steps. First, an individual mirror segment is suspended by four strings to minimize distortion on the mirror and replicate its free state and optimal figure. Second, the mirror is temporarily bonded to a strongback, essentially a flat plate with pins protruding from it. The strongback freezes the mirror segment in this optimal distortion-free state, and allows for the mirror to be transported and tested. Third, the mirror segment is then aligned to achieve optimal focus. Fourth, the mirror is permanently bonded into a mirror housing structure that supports multiple mirror segments. Finally, the temporary bonds are released, leaving the mirror fully supported by the permanent structure. This paper will focus on the last three steps of the process: the alignment, permanent bond, and transfer (release of temporary bonds).

2.1 Mirror suspension and temporary bond

In order to transport and work with the mirror segment, it needs to be mounted to a fixture. First, the mirror is hung using four strings to minimize the gravity distortion on the mirror as shown in Figure 1.

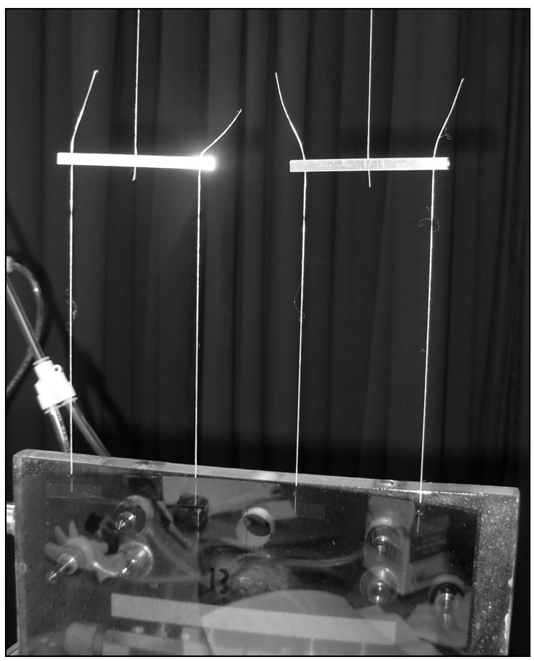

Figure 1 – Four string suspension mount

Once the mirror is hanging vertically, it is captured by a strongback. The strongback is a rectangular glass block with a set of pins protruding from its front surface. These pins are set in near-frictionless air bearings so that they apply minimal force when making contact with the mirror. The pins are bonded to the back of the mirror as shown in Figure 2, but are still able to float freely to compensate for the mirror swaying or moving. When the mirror settles into its relaxed state, the back of the pins are bonded to strongback, to freeze them in place. This sets the mirror in its hanging state where the distortion is minimized.

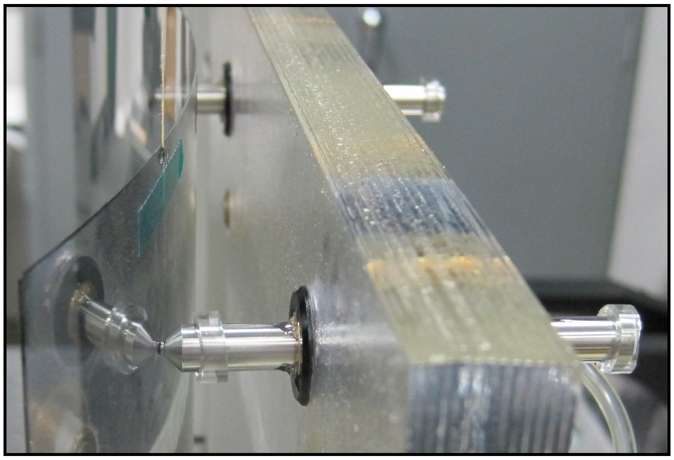

Figure 2 – Pins in air bearings bonded to mirror

The strongback enables the mirror on it to be transported, tested, aligned, and transferred onto the mirror housing.

2.2 Mirror Alignment

Once the mirror is temporarily bonded, it can be tested for surface quality, and then put into proper alignment. Finite element modeling and test data confirm that small adjustments in re-orientation in the gravity field do not distort the mirror figure significantly. The alignment is done with respect to a parallel beam light source.

A six degree of freedom hexapod is used to align the strongback with the temporarily bonded mirror. The hexapod has a repeatability of ±0.5 µm in the linear X, Y, and Z directions (see Figure 3). The controller outputs the absolute position of the hexapod in X, Y, Z coordinates to 0.1 µm. The rotational position of the hexapod in U, V, and W coordinates (see Figure 3) is reported to 10^{-4} degrees. Knowing the absolute position of the mirror to this level of accuracy enables calculations to be performed to determine the necessary adjustments for optimizing the image.

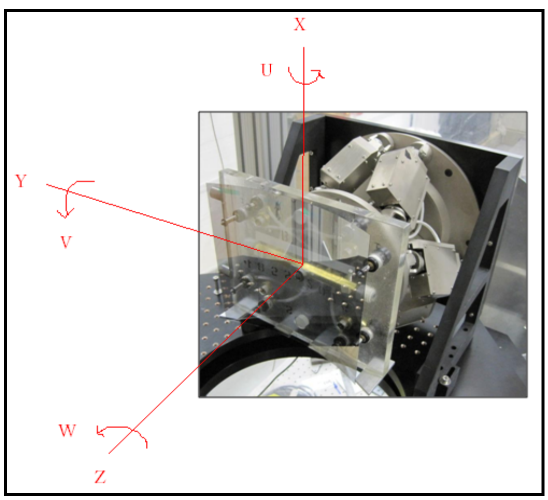

Figure 3 – Hexapod coordinate system

The alignment is mainly adjusted by tilting the mirror in the V direction (pitch), and by tilting the mirror in the W direction (yaw). The final way to obtain a better image is to adjust the focal distance by moving the CCD camera at the end of the beam. For data analysis purposes in preliminary trials, it can be desirable to move the CCD camera to get better data to better understand the process. However, when multiple mirror pairs are permanently bonded, they must all focus at the same point since there will only be one detector.

There are three main focal distances that are used for the specific mirror segment being tested. The current mandrels for slumping glass segments were designed for the earlier mission specification of an 8.4 meter focal length even though the current specification is 20 meters. The focal lengths shown in table 1 are measured from the point halfway between the primary and secondary mirrors known as the PS point to the focal point. These focal lengths were picked when the mission had chosen to go with an 8.4 meter combined focal length. Even though the new specification is 20 meters, the process is being proved out with the hardware that was built for the 8.4 meter length.

Table 1. Focal distances of various segments

Type of Segment	**Focal Distance (m)**
Primary	17.056
Secondary	5.654
Primary and Secondary	8.400

To achieve this long focal distance when the mirror is in a vertical position, a light source is positioned above the mirrors, shone downwards, and then bent 90 degrees using a 45 degree fold mirror so that it is parallel with the optical bench surface. It is then bounced back and forth using flat fold mirrors to achieve the necessary focal length. The light source is a red beam with a wavelength of 633 nm, which is in the visible light spectrum. Using visible light is a safer way to do testing than shorter wavelengths such as ultraviolet or x-ray. Also, using visible light allows for the path of the light to be detected by the human eye by using white targets in order to find the image when large adjustments are made.

The mirror reflection starts as an arc shape (similar to the shadow of the curved mirror) which becomes smaller and smaller until it focuses to a small hourglass shape as shown in Figure 4 (also known as a rotated bow-tie). Past the focus, the arc becomes inverted, and grows in size. The focus location determines one component of the alignment. The location of the center of the hourglass itself determines the rest of the alignment. The location of the center of the hourglass is characterized by performing a Hartmann test.

Figure 4 – Image of mirror reflection at focus

Due to the light source generating a beam of light with a wavelength of about 633 nm, there is a noticeable diffraction effect in the image. Because of the small cone angle of the primary mirror segment, this diffraction effect is large when measuring primary segments.

In order to achieve a good result, the mirror must be tilted at a very specific angle in which the light distribution at the focus is symmetrically distributed across the hourglass shape. A rough estimate of this symmetrical distribution of light can be done by simply looking at the image and correcting. For instance, as shown in Figure 4, the light is slightly biased towards the right side of the image, which would be corrected by changing the yaw of the mirror. Biasing towards the top or bottom of the image can be adjusted by modifying the pitch angle. Fine tune adjustments are calculated using the analyzed data. Once a Hartmann test is complete, the general shape of the data set in addition to the magnitude of the errors can be used in conjunction with a set of equations to calculate the necessary adjustments needed for the optimal result. Because the relative position of the mirror between tests is known from the hexapod coordinates, it is possible to quantitatively calculate adjustments. Once a mirror is set-up, the automation of the Hartmann test and data analysis on-site makes it possible to run a test and have results in five minutes. This allows for multiple adjustments to be made and to run iterations to perfect the alignment of the mirror segment. Previous to the use of the hexapod and automated Hartmann analysis, several days were required to align a single mirror segment.

2.3 Mirror Alignment Hartmann test

A modified Hartmann test is used to test the alignment of the mirror. The test is basically to measure focusing of the mirror by measuring the light ray from sub-apertures of the mirror being tested. In the case of segmented cylinder-like mirror shells such as those of IXO, the simplest sub-aperture is an azimuthal slit. This simplifies the test significantly as the test is then a one-dimensional test.

To perform the test, a mask is used to cover the reflection light coming off of the mirror. Only a specific slit of light is allowed to pass through the mask. The mask is then rotated to allow light from different strips of the mirror to be analyzed independently. In regards to the hourglass shaped focused image, when only a thin segment of the reflection arc is allowed to pass through the Hartmann mask, a line is displayed. When the lines formed by each stripe of the mirror are put together, they form the hourglass shape as shown in Figure 5.

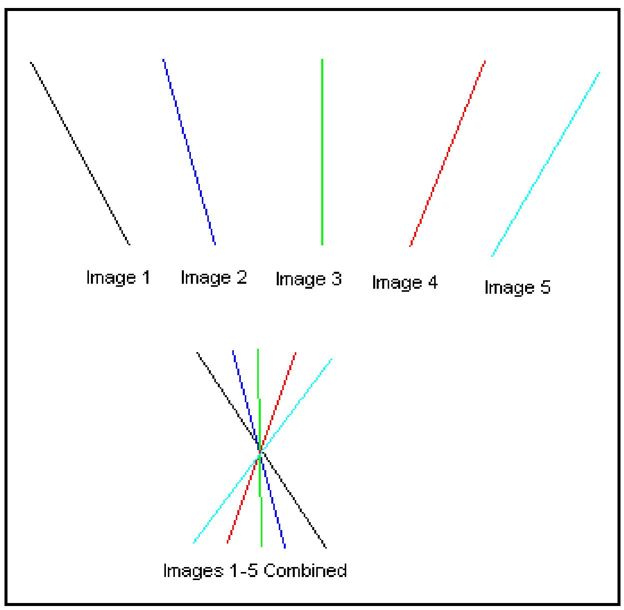

Figure 5 – Combined image explanation (only five images shown to simplify diagram)

A CCD camera is used to capture an image of each line recording the brightness value of each pixel. The theoretical centroid of the brightness values should be in the center of the hourglass. Therefore the alignment error can be determined from the deviation between the centroids of each of the separate images. The final outcome of the test is a plot showing the deviation of each centroid location from the average location as shown in Figure 6. Motorized linear stages and a rotational motor have been utilized to automate this entire test.

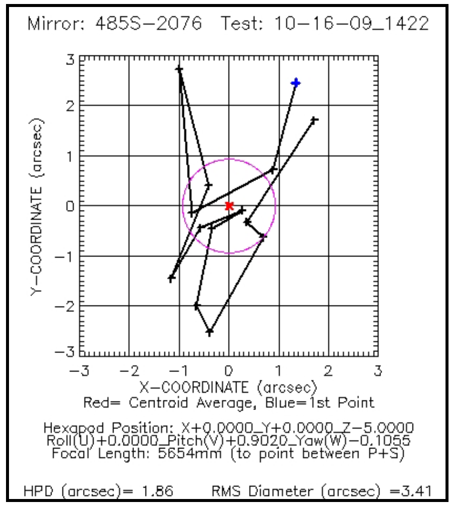

Figure 6 – Sample plot of centroids

The mirror segment alignment parameters are labeled on the graph to track settings used to achieve the image. This helps to understand what changed between trials to improve or degrade the image. The parameters are listed in five major categories. The mirror number is reported to show which mirror is being used. The test number reports the date and time the test was performed. The hexapod position shows the coordinates that the hexapod was programmed to in order to translate and tilt the mirror to the alignment used during the test. The focal length reports the distance between a fixed point P+S and the CCD camera. The point PS is a point located 24 mm above the top of the secondary mirror or 26 mm below the bottom of the primary mirror in the permanently mounted configuration. The HPD and RMS ratings give a value of the spread of the centroids which is used to rate the mirror. The HPD rating of the mirror stands for "half power diameter". It is the diameter of the circle around the average centroid that would contain half of the points. It is signified by the magenta circle in Figure 6. The blue cross signifies the first data point taken, which helps illustrate the shape of the mirror by tracking the individual points with the order they were taken in. The red x indicates the average of all the centroids.

2.4 Hartmann test data analysis

The data that is output after the Hartmann test is a set of images of single lines that when combine would form the “hourglass shape” shown in Figure 5. Each image is analyzed independently to find the angle of a line that passes through the sliver of light. This line is represented by a dashed line in Figure 7.

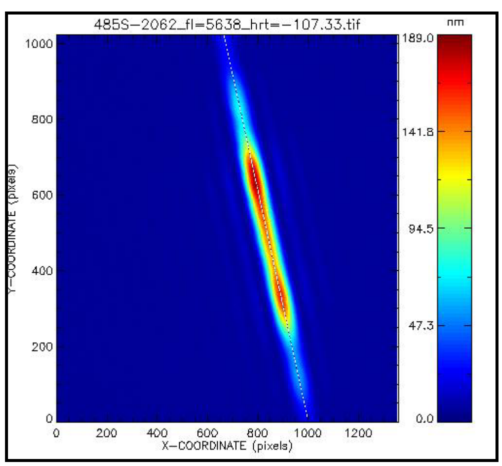

Figure 7 - Analyzed single image from Hartmann test

Once this line has been found, the points along the line are analyzed to compare the brightness of each pixel. The light intensity as a function of focal plane coordinate is shown in Figure 8. The centroid of the area under this curve is calculated to determine image's centroid. This centroid represents where the center of the hourglass is for that specific image. By comparing the centroids of all of the images, the error rating of the mirror can be determined as shown in Figure 6. Diffraction affects the result when using visible light, so the final test of the mirror alignment is done using x-rays in a vacuum chamber. X-rays have a much shorter wavelength, and the diffraction effect is essentially negligible.

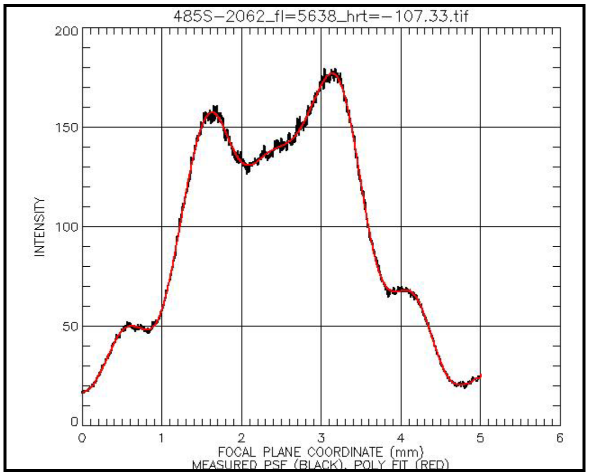

Figure 8 – Light intensity curve along sliver of light

2.5 Permanent Bonding

Once a mirror segment has been properly aligned, it is permanently bonded into a mock-up of the flight mirror module. For testing purposes, a Mirror Housing Simulator (MHS) is being used to provide bond locations similar to where they would be in the final module design. The MHS is capable of supporting three mirror pairs of different radii. The MHS is constructed of a Ti-15Mo alloy which closely matches the coefficient of thermal expansion (CTE) of D263 glass mirror segments.

Figure 9 – Mirror Housing Simulator (MHS) with two permanently bonded mirrors

There are twelve rails, six on each side to hold the primary and secondary mirrors. For current testing purposes only the rails at the four corners of each mirror are being used as shown in Figure 9. Small flat tabs slide along the rails into position behind the mirror segment as shown in Figure 10. A miniature stage is used to make the gap size between the tab and the mirror consistent to within a thousandth of an inch for all the tabs. Once in position, the tabs are secured to the rail using epoxy.

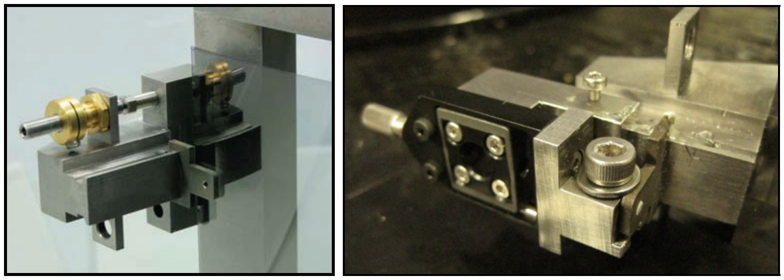

Figure 10 – MHS rail with tab and mirror (left), miniature stage moving tab along rail (right)

A closed loop system was designed for the bonding process with a laser displacement sensor (LDS) monitoring the position of the mirror to within 10 nanometers. The data from this LDS is fed into a program that controls the motion of a motorized linear stage called a nano-probe that moves the syringe in sub-micron steps to compensate for epoxy shrinkage and displacements caused by the epoxy making contact with the mirror and the tab. Since the final displacement requirement is less than 0.6 microns of movement, the process has been automated so that it can be performed "hands off" without disturbing the MHS in between bonding tabs. The syringe and nano-probe are mounted to their own tower. Before any bonding occurs, 8 LDS are set up at each of the 4 bond points for both mirrors. The bond permanent bond hardware is shown in Figure 11 below.

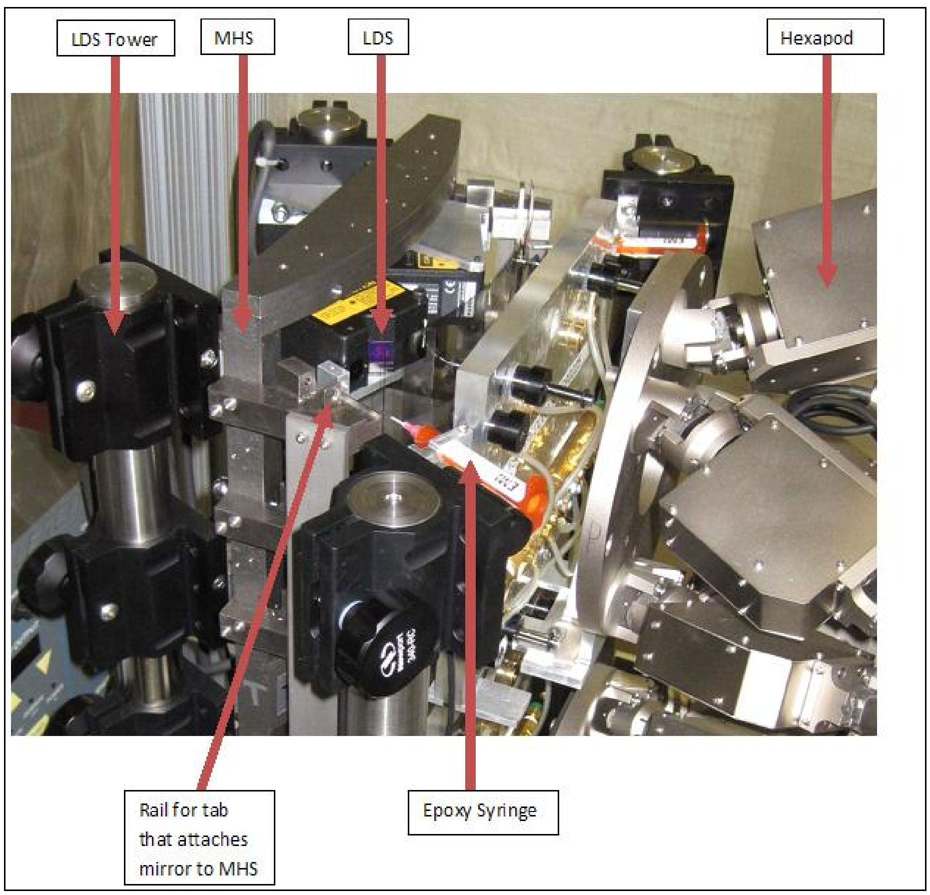

Figure 11 – Permanent bonding setup

Once the mirror has been bonded to all four tabs, the temporary bonds are broken by twisting the pins, and the strongback is removed. It has been demonstrated that breaking the temporary bonds does not damage the mirror.

2.6 Multi-Cure Bonding Technique

A new UV epoxy cure technique was created to bond the mirror to the tab while imposing less than 0.15 microns of displacement. This is the perceived allotment of shift in mirror position that would be allowed under the current error budget scenario for preserving the shape of the mirror for acceptable optical quality. The short term goal is to achieve better than 0.6 microns final displacement, but less than 0.15 microns is the ultimate long term goal. Bonding causes optical distortion due to the shrinkage of epoxy as it cures, so UV cure epoxy and Hysol 9313 have been investigated.

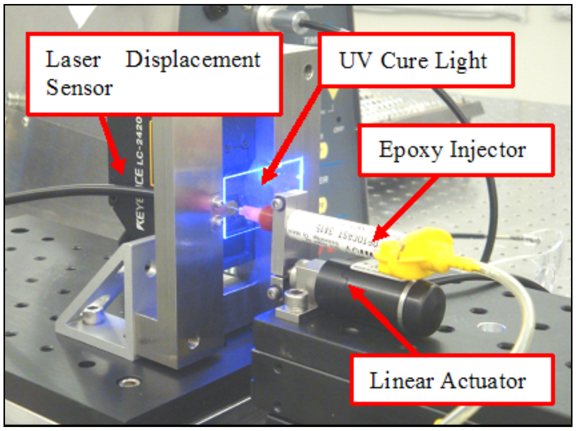

Figure 12 – Epoxy injector mounted to linear actuator for bonding test experiment

To achieve the submicron mirror displacement due to applying epoxy a "zero-displacement bond" method has been developed. A small high resolution linear actuator called a nano-probe with a resolution of 30 nm is used to move the syringe. The actuator is wired into a closed loop system utilizing a laser displacement sensor with a resolution of 10 nm. The laser displacement sensor monitors the position of the mirror and feeds it back into a program with the linear actuator. In order to compensate for the shrinkage effects of the epoxy, and keep the mirror in its initial position, the actuator is controlled. The actuator oscillates the syringe tip in and out of the tab to move the mirror using the viscous forces from the liquid epoxy. The syringe is oscillated until the mirror has reached the desired offset position. This offset is determined by how much epoxy shrinkage will occur during the cure using the UV light. This process was perfected by performing numerous trials using small microscope slide sized glass segments to simulate the mirror.

3. RESULTS

The mirror pair 485C-2058 was bonded into the MHS without adding noticeable distortion. As shown in Table 2, the results from the Hartmann tests taken before and after bonding were within the error of the measurement. This implies that negligible distortion was added during the bonding process. However with the suspension mount method, the fundamental idea is to preserve the shape of the mirror, not improve it. So if distortions are added during fabrication or temporary bonding of the mirror, nothing can be done to fix those distortions in the permanent bond process. Unfortunately, the more distortion added during the initial processes, the higher the error rating of the mirror at the alignment stage. Since errors are combined using an RSS method, the larger the initial error, the less sensitive the process is to detecting future distortions.

Table 2. Alignment results of mirror pair 485C-2058

Temporary Bond Alignment	11.4 +/- 1.25 arc-seconds
Permanent Bond Alignment	10.9 +/- 1.25 arc-seconds

In the bonding of mirror pair 485C-2058, the mirror movements were all less than or equal to 0.6 microns excluding one outlier due to a human error of monitoring the wrong sensor. FEA analyses have shown that a standard deviation in permanent bond displacement of 0.6 microns would yield a 4" HPD error which would meet the allocation allowed for the TRL 4 goal currently being pursued. The individual results for each tab bonded during the most recent trial are shown in Table 3. In all of the trials except for one that was omitted due to an error in measurement, the permanent bond successfully meets the goal of 0.6 microns. This LDS data corresponds well to the previous table which showed that the Hartmann results from the mirror segments before they were bonded, and after they were bonded and transferred were the same within the noise of the test. In future trials, a better temporary mount will increase the measurement sensitivity, and the permanent bond technique can be fully proven out. By ensuring the mirror pair does not change to within 4 arc-seconds, the mirror pair will be on track to meeting the requirements for TRL 4.

Table 3. Bonding results of mirror pair 485C-2058

	Secondary Mirror				Primary Mirror				Average	Standard Deviation
	Tab 1	Tab 2	Tab 3	Tab 4	Tab 1	Tab 2	Tab 3	Tab 4		
Mirror movement during bonding (μm)	-0.6	-0.3	-0.2	0.0	0.6	0.1	0.1	*N/A	0.27	0.24
*During bonding of tab 4, the wrong laser displacement sensor was used and therefore the movement of the mirror was not recorded accurately.										

To reach flight qualifications, a permanent bond displacement of less than 0.15 microns will need to be achieved in order to yield less than 1” HPD. A repeatable process to achieve a permanent bond displacement standard deviation of less than 0.15 microns from zero has been demonstrated in a side experiment, but has yet to be fully proven on actual mirror segments. Future work will focus on honing this technique and applying it to the mirror transfer process.

4. CONCLUSIONS

The mission requirements for IXO of large effective area and high angular resolution do not leave much room for error in the alignment and mounting of thin mirror segments. However, this has driven the design of new hardware and procedures to accommodate these challenges. The automation of the Hartmann test and on-site data-analysis has made it possible to develop an iterative process to optimize the alignment of the mirror. In addition, the automation of the bonding process has led to advances in deformation control to the sub-micron level. Given the strict error budget allowed in the alignment and bonding of a mirror segment to its permanent housing, these advances are significant. Because of the modular design of the FMA this work should apply directly to the other segments to help make this mission a reality. Future work includes bonding a mirror pair into the Mirror Housing Simulator (MHS) with an x-ray test result less than 15 arc-seconds to meet the TRL 4 requirement. Once this is accomplished, repeatability must be demonstrated by performing multiple trials. The next step will be to co-align multiple pairs of mirrors to the same nominal focal point.

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